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TITLE: Museum Visitor Preference for the Physical Properties of 3D Printed Replicas

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ABSTRACT

Within museology, the past few decades have seen a resurgence in focus on the experience of the museum visitor and what museum professionals can do to provide more meaningful, memorable visits. One method of achieving this is through multisensory experiences, encouraging museum visitors to use a range of senses to explore an exhibition, a process known to facilitate the generation of memorable experiences. However, as many museum objects are fragile and potentially irreplaceable, surrogates must be created in order to encourage such interaction within exhibitions. Use of 3D printed replicas is one approach, creating risk-free accurate copies of rare objects for visitors to handle. Despite the popularity of this technique, little user experience research has been carried out investigating the perspective of visitors and as a result, little guidance on best practices exist at this stage. Here, we present an investigation into visitor preference of the physical properties of 3D printed replicas, using semantic differentials, exploratory factor analysis and other statistical approaches. The study finds that the most important aspect of 3D prints for museums visitors was that of verisimilitude, visitors dominantly preferring prints that best represented the original specimen, with factors including the robustness of a 3D printed replica and its quality being important to museum visitors, although the importance of these to visitor preference varied. Also discussed are a number of further questions of key interest to heritage workers, including the perspective of the varied nature of museums audience, blind and partially-sighted visitors and their impact on learning experiences.

Keywords: 3d printing, multisensory interaction, heritage, exhibition design, user experience

INTRODUCTION

The question of touch is a prevalent issue within museum studies that has become increasingly relevant over the past few decades (Baker, 2015; Radywyl et al. 2015) as museums have moved towards creating more user centred experiences over didactic ones (Hooper-Greenhill, 2000; Marchietti, 2013). *Multisensory experiences*, those in which visitors make use of a range of senses beyond sight, have become increasingly important (Paris, 2002; Pye, 2008; Chatterjee, 2008; Levent and Pascual-Leone, 2014) and many calls for the overhauling of the visually-dominant ‘Glass-Case Paradigm’ display method have been made (Dudley, 2010; Petrelli, 2013; Wilson et al. 2017a). The provision of multisensory applications within collections-based museums is still limited (Bacci and Pavani, 2014), although the situation is slowly improving as professionals apply themselves to the issue. Approaches include the creation of touchable exhibits, (Levent and Pascual-Leone, 2014; Schorch, 2014; Kuo et al. 2016), touch tours and handling sessions, the latter providing visitors the opportunity to interact with the collections and particularly noteworthy for allowing access to blind and partially sighted (BPS) visitors (Phillips, 2008; Candlin, 2010). However, the challenge still remains for museums to provide permanent facilities for interaction with specimens for visitors in the exhibition space, a problem for museums whose policy is dominated by a need to conserve the rare objects in their collections.

A way in which this issue is being slowly overcome is through the use of 3D printing (Wilson et al. 2017a). Many institutions around the world are utilising this evolving technology for creating engaging multisensory experiences for museum visitors. 3D printing, is a process in which complex three-dimensional objects can be made via the serial stacking of layers of material to create a 3D object (Gibson et al. 2015; Torabi et al. 2015). Many authors highlight the potential of this approach for outreach through disposable replicas of valuable artefacts (Rahman et al. 2012; Sportun, 2014; Scopigno et al. 2014; Laycock et al.

2015) and use in general display (Allard et al. 2005; Scopigno et al. 2017). Others demonstrate the potential of this technology using ‘smart replicas’, 3D printed models with implanted chips that trigger auxiliary content within a museum exhibition (Capurro et al. 2014; Marshall et al. 2016; Balletti et al. 2017). Others use 3D prints within standard exhibitions to allow visitors hands on experience with 3D printed replicas during their visit (Dima et al. 2014; Schwandt and Weinhold, 2014; Callieri et al. 2015). 3D printed replicas and tactile reliefs have also been used to assist BPS visitors in interpreting images, paintings and large structures (Neumüller and Reichinger, 2013; Neumüller et al. 2014; Götzelmann, 2017).

Despite this surge in activity in the generation of 3D printed content for museums and the general positivity around their potential use, research considering the needs of the museum visitor is limited, as highlighted by Neumüller et al. (2014) and Wilson et al. (2017a). Di Franco et al. (2015) for example carried out a study comparing user opinions of standard glass case methods against VR and 3D printing media, finding that visitors preferred less authentic representations, provided that they allow them to engage more with the object. Wilson et al. (2017a) also carried out a front-end evaluation looking into the potential of this approach, of museum visitors’ opinions on the introduction of 3D printed replicas into the museum, finding extremely positive support of visitors wanting to see such replicas in exhibitions. These two articles represent the extent of research into this subject however. Neumüller et al. (2014) also noted the lack of research that has been carried out within this area, stating that more needs to be done to establish basic guidelines with regards to workflows and methodologies. This highlights a major issue prevalent within the discipline, namely a need to identify the best approaches and practices with regards to the use of 3D printed replicas.

In this article we seek to further explore the user experience of museum visitors with regard to touchable 3D printed replicas, evaluating user preference of the physical properties of 3D prints to best understand the preferences of the museum audience. To do this, we utilise a mixed-methods approach rarely used in museum evaluation with a suite of statistical and standard user experience (UX) methods, adapted from the work of Wellings et al. (2008; 2010; 2012). A variety of different modes of 3D printing were analysed, with museum visitors from a wide variety of age groups voicing their preference and concerns on different printing modalities and their properties.

METHODS AND MATERIALS

Materials

The materials used in this project were similar to those utilised by Wilson et al. (2017a), and derived from the OUMNH specimen of *Phascolotherium bucklandii*, the lower jawbone of a fossil mammal that has been in the museum's collections for approximately, 200 years (Figure 1A) (Howlett et al. 2017). The specimen was scanned for 3D printing using X-Ray Computed Tomography (XCT) in a Zeiss XRadia 520 Versa CT scanner at the University of Warwick.

From the scan data, six 3D prints representing different modes of 3D printing were selected and created to represent different printing technologies and materials of relevance to handling, including Fusion Depositional Modelling (FDM), Stereolithography (SL), Laser Sintering (LS), and Powder-Based 3D printing (3DP) (Figure 1B). These are, Clear Resin (SL), Colour Sandstone (3DP), Painted Resin (SL), White Resin (SL), Blue Plastic (FDM), and Stainless Steel (LS). For information on the above printing methods, see Mahindru and

Mahendru (2013), Torabi et al. (2015), and Gibson et al. (2015) for technical reviews and Scopigno et al. (2014; 2017) for a review in reference to cultural heritage.

Participants

A total of 140 participants were sampled from within the museum environment at the Oxford University Museum of Natural History (Figure 2). The sample consists dominantly of females (58%) (n = 79) over males (41%) (n = 56) (Figure 2A), the opposite of Wilson et al. (2017a) despite an identical method of sampling. One participant chose 'other' as their gender (1%) (n = 1) and two participants chose not to disclose their gender (1%) (n = 2).

Age ranges show highest participation in the 08-16 (25%) (n = 36), 35-44 (31%) (n = 45), and 25-34 (14%) (n = 19) categories (Figure 2B). Other age groups show more limited representation, with 45-54 at (11%) (n = 16), 17-24 at (6%) (n = 8), 55-64 at (6%) (n = 9), and 55-64 at (4%) (n = 6). One participant chose not to disclose their age (1%) (n = 1).

Data Collection Procedure

Convenience sampling-based approach was used within the main exhibition hall at the Oxford University Museum of Natural History. The researcher sat at a workshop and was approached by potential participants who were encouraged to handle the prints and discuss the subject of 3D printing. Participants were invited to complete a short guided questionnaire on the subject of visitor preference of 3D prints. Only ages of 8+ were permitted to ensure that all participants could complete the task to a satisfactory level. This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board at the University of Warwick. Informed consent was obtained from each participant. In this questionnaire, the visitors were first asked to handle all of the prints to get used to the range on offer and start forming impressions of each. Once the

participant was satisfied, they were given a questionnaire and asked, for each 3D print presented in a random order, to complete a set of 12 continuous semantic differential scales measuring physical variables. Scale headers were randomly flipped and semantic scales were randomly ordered throughout the questionnaire.

Once this was done for each of the six prints, the participant was then asked to rate each of the 3D prints along a continuous semantic scale based on their preference of each relative to the others. Finally, they were asked to provide a few reasons why they preferred the one they rated the highest and why they did not prefer the one they rated the lowest.

This was done using a similar approach to Low and Lamb (2000), among other authors. Firstly, interviews were carried out using an identical sampling method as above on 15 museum visitors, asking them to describe the six 3D prints in terms of their surface texture, weight, and aesthetic qualities. These were recorded and transcribed before subjected to keyword analysis, in which adjectives, descriptive nouns and descriptive verbs were extracted. These were then ordered by frequency and the most popular descriptive words compiled into a shortlist of 20 word pairs.

This shortlist was then subjected to a pilot test ($n = 26$) to refine the methodology. These were subjected to reliability analysis using Cronbach's alpha (α) for each 3D print, and all met the minimum reliability value of between 0.7 and 0.8 (Tavakol and Dennick, 2011; Field et al. 2012) with the exception of the stainless steel print (Table 1). From this, the most reliable scales were picked to create a final list of 12 scales. These were: Good Quality – Bad Quality, Unclear – Clear, Cheap – Expensive, Soft – Hard, Light – Heavy,

Figure 1: *Phascolotherium bucklandii*, Broderip 1838. A) The *P. bucklandii* specimen housed at the OUMNH. Recovered from the Stonesfield Slate. OUMNH J.20077. Specimen Scale bar equals 5mm. B) The six 3D prints used as part of this analysis. From the left to right from the top these are: Clear Resin, Colour Sandstone, Painted Resin, White Resin, Blue Plastic, and Stainless Steel. All prints are scaled up from the original by a factor of roughly six.

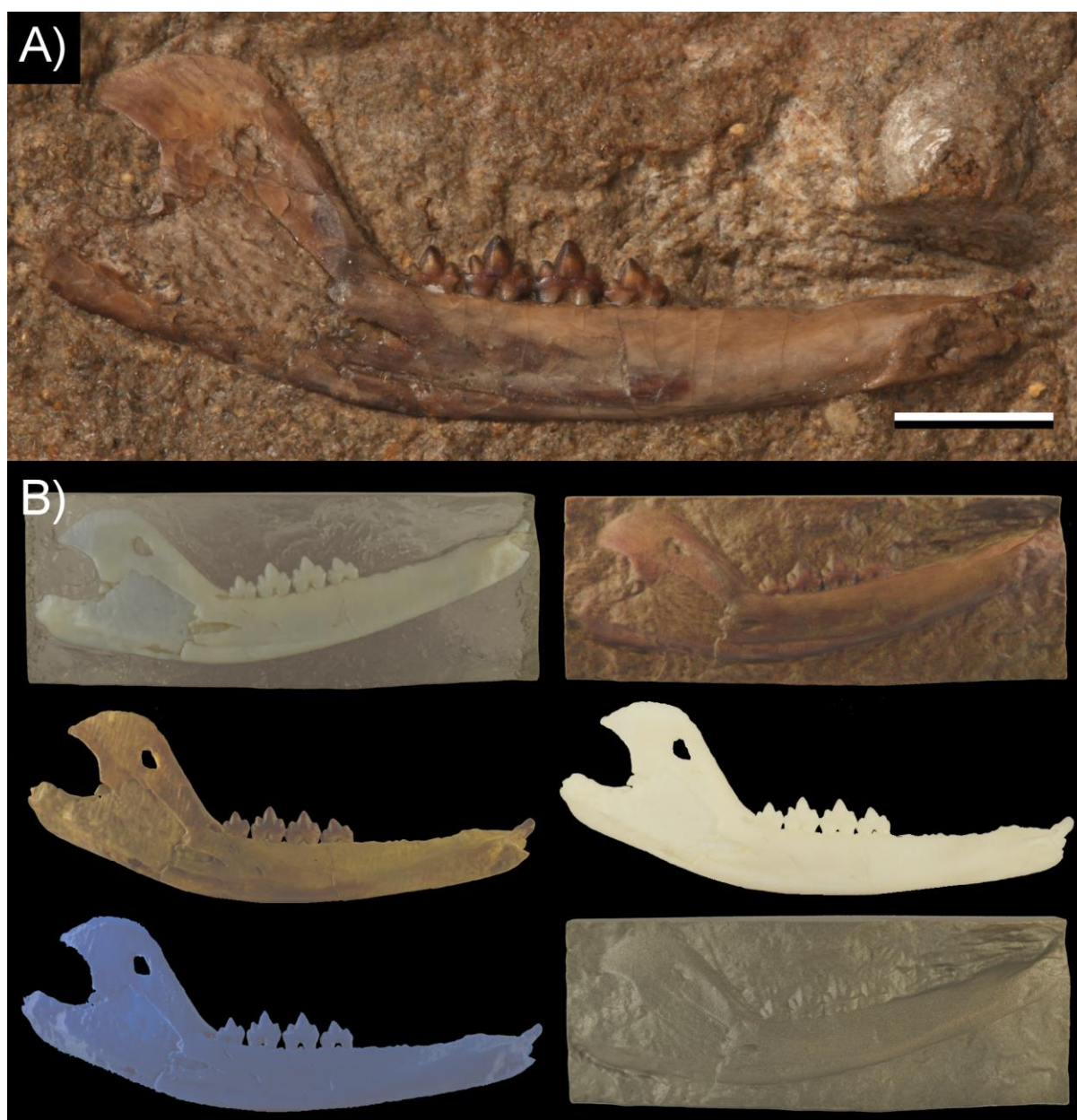
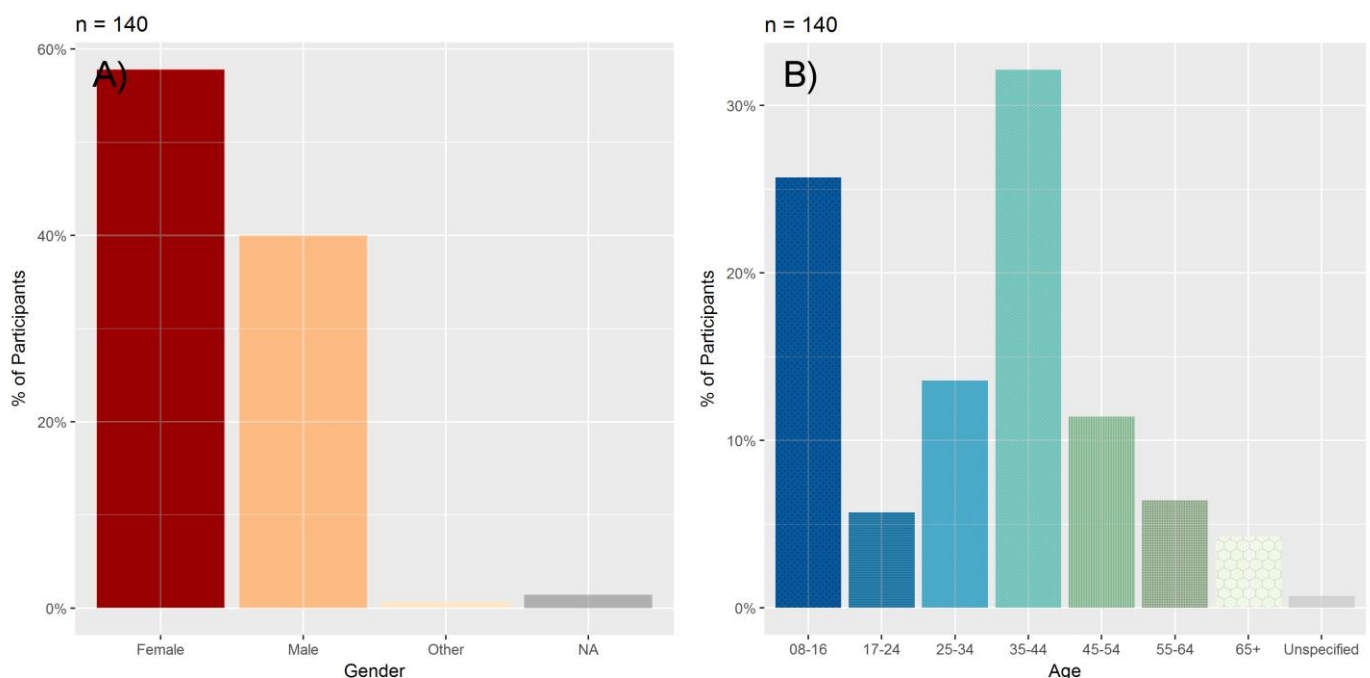


Figure 2: Demographics of the Sample. A) Gender distribution of the sampled participants.
 B) Age distribution of the sampled participants. Colours and patterns represent age groups.
 Royal Blue (Dots) = 08-16, Cerulean (Horizontal) = 17-24, Light Blue (Diagonal Left) = 25-34, Turquoise (Diagonal Right) = 35-44, Green (Vertical) = 45-54, Olive Green (Cross-hatched) = 55-64, and Light Green (Hexagonal) = 65+. Created using ggplot2 in R.
 Weak – Strong, Brittle – Durable, Rough – Smooth, Glossy – Matte, Unrealistic – Realistic, Undetailed – Detailed, and Boring – Interesting.



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182 Content Analysis

183 The comments on preference for each participant's most and least preferred 3D print were
 184 subjected to content analysis. The unit of analysis were defined as each logical clause in the
 185 participants written responses and all comments were subjected to coding to create coding
 186 schemes.

Table 1: Cronbach's α Reliability of Semantic Scales. The scale reliability for each of the 3D prints based upon pilot testing of the semantic scales ($n = 26$) and final study ($n = 140$). Minimum required values for Cronbach's α is 0.7.

	<i>Pilot Alpha (α)</i>	<i>Final Alpha (α) *</i>
Clear Resin	.83	.69
Colour Sandstone	.78	.8
Painted Resin	.82	.72
White Resin	.85	.77
Blue Plastic	.75	.78
Stainless Steel	.68	.71
Average	.785	.745

* Two Scales (Smooth – Rough and Glossy – Matte) dropped to Achieve Reliability

These coding schemes were generated using inductive category creation, defined by reading through the responses of all participants for both positive and negative statements and attempting to define each answer to create a coherent, mutually exclusive coding scheme. These were then subjected to inter-rater reliability analysis using Krippendorff's alpha (α) (Krippendorff, 2013). This was carried out on 20% of the participant's responses ($n = 29$ or 112 Units) by the code creator and an inter-rater, computing an initial α of 0.796. This value fell just short of the desired rating of 0.8, but above the minimum rating of 0.7 (Krippendorff, 2009; 2013). In order to achieve the desired value, both raters met and discussed and reconciled potential errors. This reconciled data computed an α of 0.868, exceeding the requirement and being indicative of a reliable coding scheme.

RESULTS

Correlation between Semantic Scales and Preference

Each scale was tested for normality prior to statistical analysis to determine which methods should be applied, using the Shapiro-Wilk Normality test. In every case the test returned a significant result (Table 2), indicating that all scales significantly deviated from normality and thus could not be tested using standard parametric approaches. Thus, Spearman's rho (ρ) was chosen to deal with this violation of normality.

In total, a number of strong, significant correlations can be observed between the semantic scales and preference (Table 3). For the total group data, Bad Quality – Good Quality, Unclear – Clear, Unrealistic – Realistic, Undetailed – Detailed, and Boring – Interesting appear to be strongly correlated with preference. Weaker correlations can be observed between Cheap – Expensive, Rough – Smooth, and Light – Heavy, the latter having an extremely weak negative correlation. The remaining variables; Soft – Hard, Weak – Strong, Brittle – Durable, and Glossy – Matte, all show insignificant correlations with preference. When the semantic data is divided into coarse age bins, differences in correlation can be observed. In the 08-16 age bracket, correlation values are lower on the whole compared to the total group and 17+ categories. For these younger visitors, strong positive correlations are again found for Bad Quality – Good Quality, Unclear – Clear, Cheap – Expensive, Undetailed – Detailed, and Boring – Interesting. Of these, Bad Quality – Good Quality, and Boring – Interesting correlate the highest by a large margin. Weaker correlations can be found between Brittle – Durable, Unrealistic – Realistic, Weak – Strong, Soft – Hard, and Glossy – Matte, the latter being a negative correlation. The remaining variables; Light – Heavy and Rough – Smooth show no significant correlation with preference.

Table 2: Shapiro-Wilks Normality Tests for Semantic Scale Data. Normality tests for each semantic scale measured including preference. All scales significantly deviate from normality and needed to be analysed using non-parametric analyses.

	<i>Shapiro-Wilk Test (W)</i>
<hr/>	
Bad Quality – Good Quality	.89 ***
Unclear – Clear	.91 ***
Cheap – Expensive	.96 ***
Soft – Hard	.90 ***
Light – Heavy	.87 ***
Weak – Strong	.90 ***
Brittle – Durable	.90 ***
Rough – Smooth	.96 ***
Glossy – Matte	.94 ***
Unrealistic – Realistic	.90 ***
Undetailed – Detailed	.90 ***
Boring – Interesting	.90 ***
Preference	.90 ***

* $p < .05$ ** $p < .01$ *** $p < .001$

By comparison, older age groups show contrasting correlations to preference. Positive correlations between Unrealistic – Realistic and preference across the 17-34, 35-54 and 55+ age groups are significantly stronger than in the 08-16 category as well as Undetailed – Detailed, Unclear – Clear, and to a lesser degree, Boring – Interesting. Weaker positive correlations can be observed between Cheap – Expensive and Rough – Smooth, the latter being uncorrelated within the 35-54 age category but are negatively correlated in 17-34 and 55+. A weak negative correlation is observed between Soft – Hard for age groups 17-34 and

35-54 but is non-significant in 55+, inverted from the weak positive correlation of the 08-16 age group in addition to Light – Heavy. Light – Heavy also appear to be negatively correlated for younger adults (17-34 and 35-54) while uncorrelated in elderly visitors (55+). Compared to the 08-16 age group, the remaining variables show insignificant correlations, with the exception of Rough - Smooth in the 17-34 and 35-54 categories with are positively correlated, strongly in the case of the 17-34 age group. This indicates a preference in younger adults towards smoother prints.

In total, strong correlations between the semantic scales and preference of 3D print types can be observed. The strongest correlates across age groups are Bad Quality – Good Quality, Unclear – Clear, Unrealistic – Realistic, Undetailed – Detailed, and Boring – Interesting. Realism, Clarity, and Detail correlate much more highly in adult age groups (17+) while correlations in the 08-16 category are weaker on the whole. Some variables correlate differently between age groups; Soft- Hard, Weak – Strong, and Brittle – Durable being weakly positively correlated in the 08-16 age category while being either negatively correlated or insignificant in the adult (17+) age categories.

Hedonic Comparison Between 3D Prints: Friedmann's Anova

The data violated the assumption of normality and Levene's test showed that the variances between preference values for each prints were significantly different $F(5,834) = 9.17, p = <0.0001$ and thus also violated the assumption of homogeneity of variance. As all cases were judged by the same participants, Friedmann's ANOVA was used (McCrum-Gardner, 2008; Field et al. 2012).

Hedonic data for the 3D prints can be found in Table 4. In raw mean values, the most preferred 3D print was the painted resin ($x = 80.5 \pm 4.0$), closely followed by the Clear Resin

Table 3: Correlation between Semantic Scales and Preference. Correlations for three groups, the total group of all ages, age ranges 08-16 and 17-34, 35-54 and 55+. Bolded values represent correlations that are statistically significant.

	<i>Total (ρ)</i>	<i>08-16 (ρ)</i>	<i>17-34 (ρ)</i>	<i>35-54 (ρ)</i>	<i>55+ (ρ)</i>
Bad Quality – Good Quality	.52 ***	.44 ***	.48 ***	.56 ***	.58 ***
Unclear – Clear	.55 ***	.39 ***	.67 ***	.57 ***	.62 ***
Cheap – Expensive	.29 ***	.37 ***	.26 ***	.25 ***	.3 **
Soft – Hard	-.03	.14 *	-.24 **	-.03	-.21 *
Light – Heavy	-.07 *	.13	-.2 **	-.13 **	-.08
Weak – Strong	.05	.21 **	-.15	.02	.06
Brittle – Durable	.05	.27 ***	-.05	-.06	.05
Rough – Smooth	.23 ***	.10	.42 ***	.24 ***	.19
Glossy – Matte	-.03	-.22 **	.07	.04	.09
Unrealistic – Realistic	.60 ***	.28 ***	.71 ***	.73 ***	.70 ***
Undetailed – Detailed	.56 ***	.30 ***	.71 ***	.64 ***	.64 ***
Boring – Interesting	.55 ***	.46 ***	.62 ***	.56 ***	.57 ***

* $p < .05$ ** $p < .01$ *** $p < .001$

($x = 78.8 \pm 3.5$). The White Resin 3D print was rated the next highest ($x = 73.3 \pm 3.7$) with the Colour Sandstone following ($x = 49.1 \pm 4.7$). Below this was the Stainless Steel print ($x = 42.2 \pm 5.1$) with the Blue Plastic 3D print being the lowest ranked ($x = 25.8 \pm 4.4$). When compared to average ratings on each scale for each 3D print (Figure 3 and Table 5), the three most popular 3D prints appear to be rated highly on Bad Quality – Good Quality, Unclear – Clear, Unrealistic – Realistic, Undetailed – Detailed, and Boring – Interesting whereas the

two lowest rated 3D prints, Stainless Steel and Blue Plastic, rate much lower on these scales. This suggests that these properties are most preferred, as corroborated above. The Stainless Steel print shows a marked contrast from the other prints, being rated highly on Cheap – Expensive, Soft – Hard, Light – Heavy, Weak – Strong, and Brittle – Durable, suggesting that properties associated with durability might be less important to preference.

Comparison of means using Friedmann's ANOVA found significant difference in the preference values of the 3D printed replicas $\chi^2(5) = 293.4, p = < 0.001$. *Post hoc* tests used with Bonferroni correction applied identified critical differences in preference between prints, highlighting three main groups of preference; A (Painted Resin, Clear Resin, and White Resin), B (Colour Sandstone and Stainless Steel), C (Blue Plastic). In all cases, the critical difference was 91.9 (Table 6).

In summary, the most popular 3D prints, all being resin-based, also rated highly on some physical properties: Bad Quality – Good Quality, Unclear – Clear, Unrealistic – Realistic, Undetailed – Detailed, and Boring – Interesting whereas the least preferred 3D prints rate much lower on these scales, forming discrete groups that rate much lower on these properties.

Figure 3: Average Semantic Plots for Physical Properties. Each box represents the average semantic scale values for a given 3D print type. Wider bars indicate 95% confidence intervals.

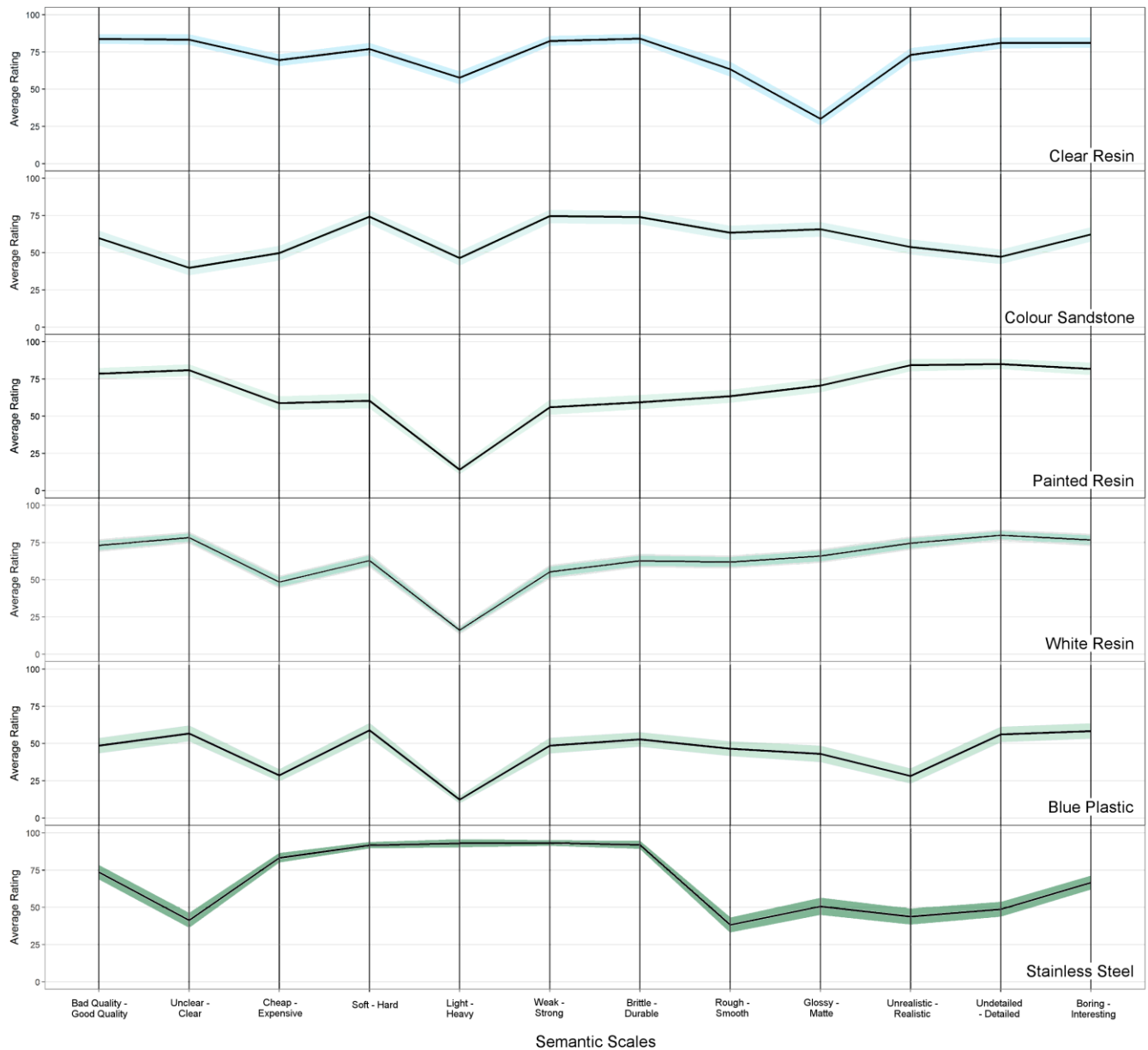


Table 4: Mean Preference Values of the 3D Prints. Mean values for overall preference of each 3D print. Mean values are accompanied by 95% Confidence Intervals. Groups represent those with non-exclusive critical difference values.

<i>3D Print</i>	<i>Mean (\bar{x})</i>	<i>SD (σ)</i>	<i>Group</i>
Painted Resin	80.5 \pm 4.0	24.0	A
Clear Resin	78.8 \pm 3.5	20.9	A
White Resin	73.3 \pm 3.7	22.5	A
Colour Sandstone	49.1 \pm 4.7	28.4	B
Stainless Steel	42.2 \pm 5.1	30.8	B
Blue Plastic	25.8 \pm 4.4	26.8	C

Note: Values converted to a 100 point scale. 95% Confidence Intervals.

Factor Analysis of Physical Properties

An exploratory factor analysis was carried out on 10 of the semantic differential items, two being removed (Smooth – Rough and Glossy – Matte) to meet minimum reliability constraints (Table 1). Oblique rotation was chosen as the variables are likely to be intercorrelated. The Kaiser-Meyer-Olkin measure verified the sampling adequacy for the analysis as KMO = .86 ('Great' according to Kaiser, 1974). All items had a KMO values > .82 with the exception of Cheap – Expensive at .60, being 'Mediocre' instead. These all exceed the minimum value of .5 (Kaiser, 1974, Field et al. 2012; Hadi et al. 2016). Bartlett's test of sphericity $\chi^2(45) = 3953.4$, $p = < 0.001$ indicated that the correlation between the items were sufficient for factor analysis (Bartlett, 1954). Analysis using oblique (oblimin) rotation identified three factors with eigenvalues over Kaiser's criterion (1.0) (Kaiser, 1960, Yong and Pearce, 2013). Scree plots identified that three factors were worth extracting (Cattell, 1966). These three factors together explained 72% of the total variance (Table 7).

The first, Factor 1 (Verisimilitude), appears to reflect closeness to the original, loading extremely highly on scales associated with realism and accuracy, including Undetailed – Detailed, Unclear – Clear, Unrealistic – Realistic, Boring – Interesting, and Bad Quality – Good Quality. Factor 2 (Robustness) instead loads heavily on Weak – Strong, Soft – Hard, Brittle – Durable, and Light – Heavy, these variables suggesting that the toughness and weight of prints are a notable factor. The final factor, Factor 3 (Quality) refers to the quality of the print, loading highly on Bad Quality – Good Quality, Weak – Strong, Brittle – Durable, Cheap – Expensive, and Light – Heavy, expensive, durable and good quality prints being an important factor for museum visitors.

Cronbach's alpha (α) of these factors show them all to be sufficiently reliable, exceeding the minimum requirement of 0.7 (Kline, 1999), Factor 1 (Verisimilitude) with $\alpha = 0.86$, Factor 2 (Robustness) with $\alpha = 0.79$ and Factor 3 (Quality) with $\alpha = 0.78$.

In total, this factor analysis expresses three underlying factors in visitor's considerations of the physical properties of these 3D prints:

- Verisimilitude (Factor 1: 33% of Variance) expresses how well the print reflects the original and how visually and tactually accurate it is.
- Robustness (Factor 2: 21% of Variance) expresses the toughness of the 3D print and how resistant it is to damage and degradation.
- Quality (Factor 3: 18% of Variance) expresses the overall quality of the piece, how well it is made in terms of strength and construction.

Table 5: Scale Average Values for each 3D Print. The average for each scale for each 3D print. Values have been converted to a 100 point scale for ease of interpretation and 95% Confidence Intervals are supplied.

	<i>Clear Resin</i>	<i>Colour Sandstone</i>	<i>Painted Resin</i>	<i>White Resin</i>	<i>Blue Plastic</i>	<i>Stainless Steel</i>
Bad Quality – Good Quality	84.3±2.6	61.4±4.3	80.0±3.2	72.9±3.7	48.6±4.6	73.7±4.4
Unclear – Clear	83.8±3.0	41.4±4.0	82.4±3.3	78.3±3.4	56.8±4.8	41.3±4.5
Cheap – Expensive	70.1±3.4	51.3±4.2	60.2±4.0	48.3±3.8	28.6±3.6	83.3±2.7
Soft – Hard	76.9±3.6	74.3±3.6	60.4±4.4	62.8±3.9	58.9±4.3	91.7±1.7
Light – Heavy	58.2±3.7	47.9±4.1	15.6±2.2	16.2±2.2	12.3±1.9	93.1±2.3
Weak – Strong	82.4±2.7	74.7±3.5	56.0±4.4	55.3±4.2	48.6±4.7	93.2±1.5
Brittle – Durable	84.5±2.6	75.5±3.6	60.9±4.1	62.7±4.0	52.8±4.4	92.0±2.2
Rough – Smooth	64.0±4.4	65.0±4.1	64.9±3.7	62.3±3.9	46.6±4.4	38.2±4.6
Glossy – Matte	30.2±3.8	65.7±4.2	70.6±4.0	65.7±4.1	43.1±5.1	50.7±5.4
Unrealistic – Realistic	73.5±3.9	55.3±4.6	85.8±3.5	74.4±3.9	28.2±4.6	43.8±4.8
Undetailed – Detailed	81.6±3.1	48.8±4.2	86.5±2.8	79.8±3.3	56.1±4.7	48.8±4.5
Boring – Interesting	81.2±2.8	62.3±4.2	81.8±3.6	76.6±3.6	58.4±4.6	66.6±4.2

Values Converted to 100 point Scales. 95% Confidence Intervals.

Content Analysis of Preference Comments

Positive Comments

The most common positive comment was that the preferred print was realistic and represented the original specimen the best (30%) (Figure 4). The second most common reason was that the chosen print was the most detailed (15%) while the third was that the preferred print was visually or tactually clear and was easy to interpret (9%). Outside of these three majority responses, a slew of other reasons were forwarded, such as providing three-dimensionality to the specimen for handling (6%), being the most interesting one (6%),

durability (6%), ease of handling and weight (5%), arbitrary preferences (e.g. ‘It’s really cool!’) (4%) and tactually (4%) or visually (3%) appealing. Other comments include the print being transparent (2%), the preferred print being more informative than others (2%), the print being shiny (1%), the weight being just right (1%), and good quality (1%), among many others.

Table 6: Friedmann’s ANOVA Critical Difference Values and Groupings. *Post hoc* using the Bonferoni correction.

<i>Comparison</i>	<i>Observed Difference</i>	<i>Difference</i>
Clear Resin to Colour Sandstone	231.5	True
Clear Resin to Painted Resin	8.5	False
Clear Resin to White Resin	76	False
Clear Resin to Blue Plastic	402.5	True
Clear Resin to Stainless Steel	288.5	True
Colour Sandstone to Painted Resin	240	True
Colour Sandstone to White Resin	155.5	True
Colour Sandstone to Blue Plastic	171	True
Colour Sandstone to Stainless Steel	57	False
Painted Resin to White Resin	84.5	False
Painted Resin to Blue Plastic	411	True
Painted Resin to Stainless Steel	297	True
White Resin to Blue Plastic	326.5	True
White Resin to Stainless Steel	212.5	True
Blue Plastic to Stainless Steel	114	True

Bonferroni Correction $p = 0.05$ *Critical Difference* = 91.9

Table 7: Factor Structure Matrix for Factor Analysis of Semantic Scales: Factor loadings for the three underlying factors extracted from exploratory factor analysis using oblique rotation (Oblimin). Loadings below .4 have been discarded.

	<i>Factor 1 (Verisimilitude)</i>	<i>Factor 2 (Robustness)</i>	<i>Factor 3 (Quality)</i>
Undetailed – Detailed	.88		
Unclear – Clear	.84		
Unrealistic – Realistic	.79		
Boring – Interesting	.76		
Bad Quality – Good	.72		.5
Quality		.87	.53
Weak – Strong		.83	
Soft – Hard		.78	.56
Brittle – Durable			.89
Cheap – Expensive		.53	.8
Light – Heavy			
Eigenvalues	3.35	2.15	1.75
% of Variance	33.0	21.0	18.0
α	.86	.79	.78

Factor Loadings less than .4 have been discarded.

Negative Comments

Amongst the negative attributes (Figure 5), the top reasons for non-preference were diametrically opposed to the positive ones, with the most common reason being that the print was unrealistic or lacked realistic qualities (21%). This was followed by lacking detail (10%) and lack of visual or tactile clarity (10%), with the print having a cheap quality to it (8%) being another major concern. As with the positive factors, a long tail of more minor reasons were then articulated, such as being too heavy (6%), artificiality (4%), and fakeness (4%), the colour being unsuitable (4%), not being interesting (3%), lacking durability (3%), poor

quality (3%), lack of tactual appeal (3%), arbitrary reasons (2%), problems with 3D printing issues (2%), and that it was too dull or not shiny (2%).

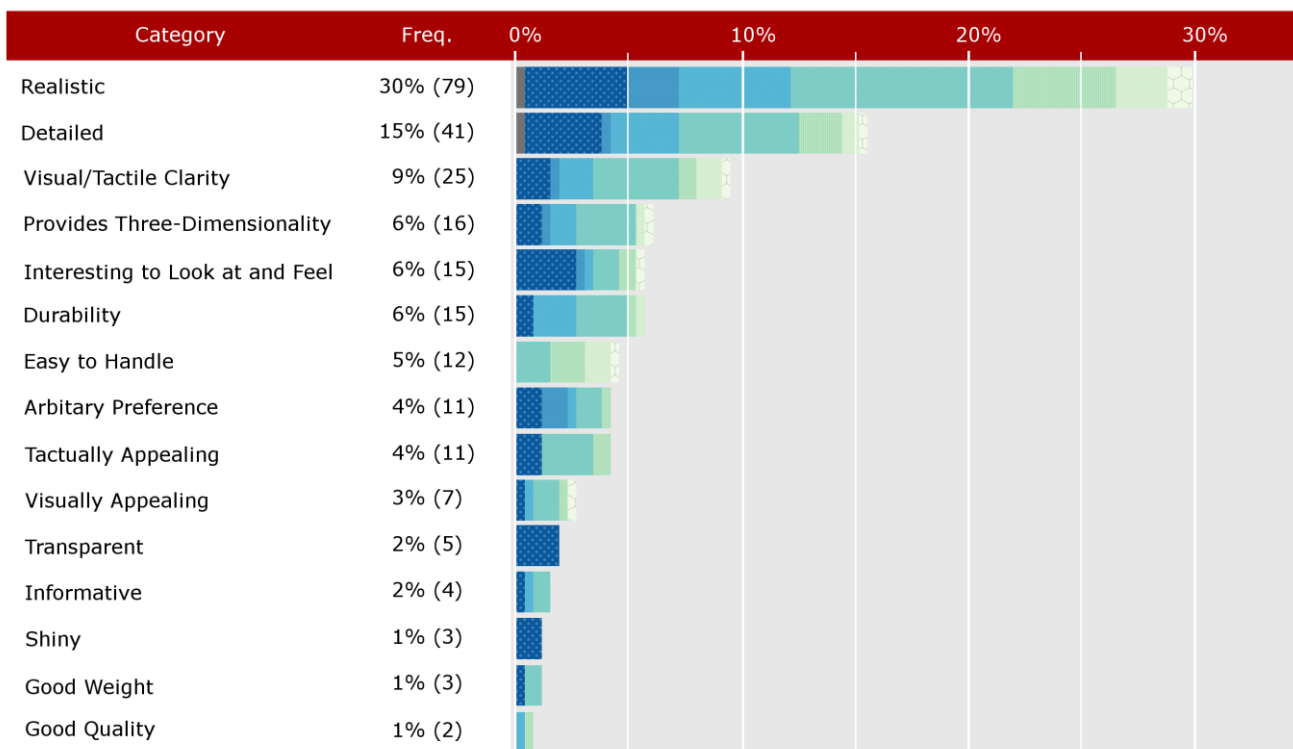
In terms of age groups, very few trends were significant. Younger visitors appeared to have a preference for more interesting 3D prints for both positive and negative reasons and were the only age group to favour prints based on their shininess or transparency. They also prioritised lack of clarity for non-preference but not for preference. This may be indicative of young visitors preferring the 3D prints that are more eye-catching.

Overall, the three most important factors for preference and non-preference derived from content analysis appear to be realism, detail, and clarity. Other more minor reasons, including; three-dimensionality, interest, durability and handling for positive and cheapness, weight and artificiality for negative. Children may be inclined towards more interesting and visually attractive pieces, although this aspect requires further work.

Summary

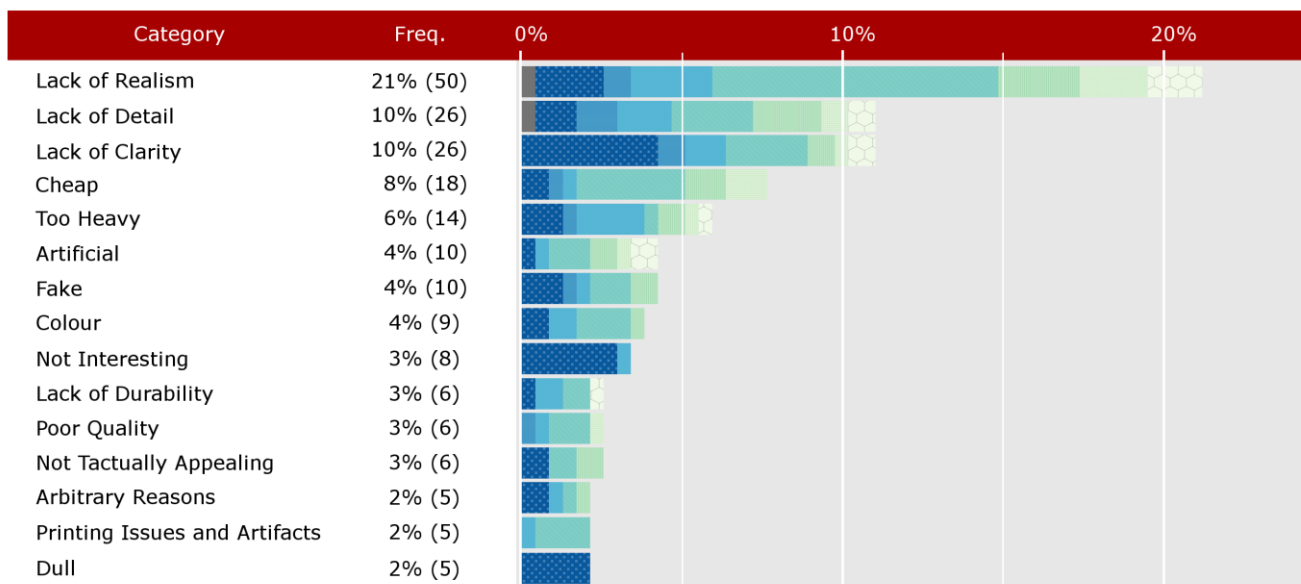
Analysis of preference and hedonic ratings of touchable 3D printed replicas finds realism, visual and tactual clarity, and level of detail seem to be key properties, correlating highly to preference and rated highly on the most preferred 3D prints. Together they constitute the top three positive and negative comments from content analysis and the dominant factor under the bracket term 'Verisimilitude'. 'Robustness', the second factor, is weakly positively correlated to visitor preference in younger visitors but weakly negatively correlated in adults. The 'Quality' of a print also appears to be of some significance also, but not as strongly as that of Verisimilitude.

409 **Figure 4: Positive Comments for Preference of Specific 3D Prints.** The top fifteen most
 410 noted reasons for preference of a 3D print. Colours and patterns represent age groups. Royal
 411 Blue (Dots) = 08-16, Cerulean (Horizontal) = 17-24, Light Blue (Diagonal Left) = 25-34,
 412 Turquoise (Diagonal Right) = 35-44, Green (Vertical) = 45-54, Olive Green (Cross-hatched)
 413 = 55-64, and Light Green (Hexagonal) = 65+ and Grey = Undisclosed. Created using ggplot2
 414 in R.



415

Figure 5: Negative Comments for Preference of Specific 3D Prints. The top fifteen most noted reasons for non-preference of a 3D print. Colours and patterns represent age groups. Royal Blue (Dots) = 08-16, Cerulean (Horizontal) = 17-24, Light Blue (Diagonal Left) = 25-34, Turquoise (Diagonal Right) = 35-44, Green (Vertical) = 45-54, Olive Green (Cross-hatched) = 55-64, and Light Green (Hexagonal) = 65+ and Grey = Undisclosed. Created using ggplot2 in R.



DISCUSSION

The importance of the verisimilitude to the original of touchable 3D printed replicas has been noted in the past albeit from rather more anecdotal sources. Wilson et al. (2017a) for instance concluded from interview data on museum visitor opinions of 3D printed replicas that some visitors strongly emphasised the importance of realism and that they should be as close as possible to the feel of the original. Similar opinions are expressed by BPS visitors as highlighted by Candlin (2003). In both studies, some visitors emphasized the importance of thermal properties within these 3D prints, highlighting the need to provide authentic objects. Di Franco et al. (2015) found that authenticity of an object is an important factor too, but their study placed less emphasis on it, finding instead that the opportunity to gain knowledge

is far more important than realism. However, there are some notable exceptions to this concept. For BPS visitors, there is often a need to emphasize tactual clarity over detail and many objects, particularly in 3D printed reliefs of artworks or paintings, are often simplified or textured to be more readily perceivable by blind folk (Eriksson, 1999).

Robustness on the other hand appears to be of less concern to the museum visitor. This property is uncorrelated across the whole group sample while being only weakly to moderately positively correlated to preference in the 08-16 category while weakly negatively or uncorrelated in older age groups. It is unclear why children would have a preference towards robust 3D prints while the negative correlation to preference in adults can be put down to safety concerns when handling heavy or tough objects. Weight also appeared to be a concern that emerged from the content analysis, being the fifth most commonly cited reason for non-preference (6%) while durability (6%) and ease of handling (5%) were the seventh and eighth most commonly cited reasons for preference. This shows that the toughness, weight and ease of handling of a print is also of some concern to museum visitors although arguably to a much lesser degree than verisimilitude to the original. Considering that the stainless steel print, the most robust one, was also much less favoured than the more fragile resin prints, this creates a dichotomy between robustness and preference, where tougher prints better capable of surviving handling may be less preferred for handling in general.

The quality of printing materials is another issue of concern. This factor, while explaining the lowest proportion of variance of the three, emphasizes the expense of the print and its perceived quality in terms of weight and toughness. Quality and expense both correlate positively in the total group although, in the content analysis, reasons pertaining to quality or expense in positive preference are rarely expressed. Quality is far more of a concern with regard to negative responses, cheapness (8%), fakeness (4%), poor quality (3%), and printing issues and artefacts (2%) all being reasons cited for non-preference of a

specific 3D print. Thus it appears that having a good quality print is not necessarily important for museum visitors, provided that it is at least of sufficient quality. However, a poor quality replica is a cause for concern and will be much less preferred by museum visitors. Thus, a minimum standard of quality for touchable 3D printed replicas needs to be achieved.

More significant however is the lack of research into the use of 3D printing in museums (Neumüller et al. 2014; Wilson et al. 2017a). Other than very anecdotal evidence for such preference, no prior robust research into visitor preference for tangible 3D prints exists. This study presents a first foray into understanding the perspective of the museum visitor with regard to these prints and can start to highlight the key needs of museum visitors with regard to this technology. It is possible however, based upon the evidence presented in this article, to begin to develop best practice guidelines for the design of 3D printed replicas.

Further Questions

While this analysis has revealed some key considerations on audience preferences of touchable 3D prints for museum visitors, there are a number of questions that need further exploration.

One question that merits exploration is the effectiveness of using 3D prints within museum exhibitions. Wilson et al. (2017a) demonstrated that museum visitors would be interested in seeing such replicas within the museum environment but little research has been carried out into how much of a learning benefit to museum visitors this approach would generate. The subject of multisensory interaction and learning in museums in general is currently an area of considerable interest. The shift towards visitor-centred learning in museum education over the past few decades has encouraged the creation of more visitor-focused museum experiences (Hooper-Greenhill, 2000; Marchietti, 2013; Dudley, 2015). An

emerging facet of this has been the rise in popularity of Object Based Learning (OBL), a learning approach derived from the experiential learning model (Kolb, 2015) that advocates student-centred learning through direct interaction with an object, resulting in meaningful acquisition of knowledge and strong memory generation (Paris and Hapgood, 2002; Chatterjee, 2010; Ward, 2014; Chatterjee and Hannan, 2015). Anecdotal evidence certainly appears to support the idea that museum visitors enjoy and learn much from such multisensory experiences (Rahman et al. 2012; Schorch, 2015) and more systematic evaluations also appear to support such inferences (Davidson et al. 1999; Sharp et al. 2015; Kuo et al. 2016). Neuroscience research on learning also supports a connection between multisensory learning and memory encoding (Spence and Gallace, 2008; Lacey and Sathian, 2014; Ward, 2014; Reeve and Woollard, 2015). Implementations of 3D printed examples of multisensory experiences also seem to be successful although, but to date only simple investigations into user experience (Dima et al. 2014; Marshall et al. 2016) and recommendations of its use have emerged (Rahman et al. 2012; Leakey and Dzamabova, 2013; Laycock et al. 2015; Du Plessis et al. 2015; Wilson et al. 2017b). As yet, little is known about how useful 3D printed replicas are as pedagogical tools for museum learning and user experience and thus, investigation into how 3D printed replicas can enhance the learning experience of visitors is required.

Another consideration is that of the varied nature of the museum audience. This analysis highlights that different age groups, particularly younger visitors and older visitors appear to have diverging opinions. This suggests that one catch-all solution is too simple. This study did not cover the entire spectrum of younger museum visitors and thus it is only reasonable to assume that visitors below the sampled age will likely have different opinions again, as younger visitors in this study seemed to have a preference towards more eye-catching 3D printed replicas. Further complicating this is the fact that research shows that

young children generally have greater difficulty in differentiating between real and fake objects up to the age of approximately 10 or 11 (Evans et al. 2002). The danger of this is that using a more diagnostic 3D print that is less realistic may deceive such children and hinder the interpretive process and thus, the perceptions of younger audiences must be ascertained.

Another further consideration is that of BPS visitors, an often marginalised community within museums due to an overall lack of provision in the past (Candlin, 2003; 2006). In the UK, legislative pressure over the past few decades has seen a redoubling of effort in museums provide more for their disabled public, including BPS visitors efforts in the UK (Disability Discrimination Act, 1995; Equality Act, 2010) and many institutions now provide frequent touch tours for BPS visitors (Candlin, 2010; Payne, 2012; Levent and McRaine, 2014). In addition, other museums provide tactile images for visitors (Neumüller and Reichinger, 2013; Neumüller et al. 2014; Götzelmann, 2017). However, these activities are typically run as one-off events and permanent provision within exhibition spaces for such visitors is still limited. As highlighted by many authors (Wilson et al. 2017a, Neumüller et al. 2014; Scopigno et al. 2017; Stanco et al. 2017), 3D printed replicas are theoretically a perfect way to allow BPS visitors to access collections using senses mandatory to their understanding of the world around them, especially with items too delicate to be handled by the untrained visitor. A major question though is how do the needs of a BPS visitor differ from those of other visitors? This article identifies the preferences of a sample of sighted museum visitors but for those who rely solely on touch to interpret an object, it raises the question of how important tactile properties are to their understanding of an object and is a subject area worthy of exploration.

Overall, this article has hopefully provided an initial understanding of the needs of the museum visitors with regards to touchable 3D printed replicas and some initial thoughts and ideas in choosing the correct material properties that appeal to visitors. This is only the first

stage of many however and further exploration is needed to better understand how the user experience of museum visitors from all demographics and backgrounds can be best addressed.

CONCLUSIONS

Mixed method analysis revealed that the most important feature for museum visitors was that of the verisimilitude of the 3D print to the original object in terms of traits such as realism, detail, and visual/tactile clarity. The robustness of a 3D print was also a factor but seemed much more poorly correlated to preference, being less of an important factor to older museum visitors but more important for younger visitors. Finally, the quality of a 3D print was a matter of concern for visitors, the quality, and perceived expense as well as its tactile quality being important for museum visitor preference. As a result, higher quality and more verisimilar prints had much higher preference than other print modalities.

Further exploration of the findings of this article are also noted, including the need to evaluate the effectiveness of this approach within the museum environment from both a museum learning and user experience perspective and the need to identify the preferences of a number of key groups, including younger visitors and BPS visitors, with regard to touchable 3D printed replicas.

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